ARMY RESEARCH LABORATORY

Application of an Analytical Model for Ballistic Penetration to Composite Targets

by S. R. Bodner
and A. M. Rajendran

ARL-TR-1383

June 1997

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

ARL-TR-1383 **June 1997**

Application of an Analytical Model for Ballistic Penetration to Composite Targets

S. R. Bodner
Israel Institute of Technology

A. M. Rajendran
Weapons and Materials Research Directorate, ARL

Abstract

This report presents the procedures developed for adopting a two-dimensional (2-D) analytical model of ballistic penetration and perforation in isotropic targets to target plates of composite materials (e.g., glass [fiber] reinforced plastics [GRP]). The depths of penetration in S-2 glass fiber/polyester matrix composite laminates were calculated using this analytical model and compared with the measured data. The initial formulation is based on blunt-nosed rigid projectiles and normal impact velocities up to about 1 km/s. Some preliminary results are described, and directions for further investigations are indicated. This report also briefly reviews penetration mechanisms in GRP laminates and some experiments and analytical/computational modeling efforts by other investigators.

Acknowledgments

The authors gratefully acknowledge the funding support of Dr. James Thompson of the Tank Automotive Research, Development, and Engineering Center (TARDEC) in Warren, MI. We also appreciate Dr. Shun-chin Chou of Weapons and Materials Research Directorate (WMRD) for his encouragement and technical discussions relating to this technical report.

INTENTIONALLY LEFT BLANK.

Table of Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

1. Introduction

Glass (fiber) reinforced plastic (GRP) composites are becoming increasingly popular in various industrial and military applications due to their particular physical and mechanical properties and tailorability to suit the requirements of specific applications. Composite materials offer a host of material variables that can be incorporated into the design of armor, and the designer is often faced with the challenge of designing the most optimum laminate configuration for the specific armor application. However, to determine the most optimum configuration from the multitude of possible combinations by experiments alone is prohibitively expensive and time-consuming. Thus, it is extremely important to develop analytical or numerical models to accurately predict the response of these composite armors under projectile impact and penetration.

Until now, the bulk of the work on modeling has focused on developing empirical models for engineering purposes. A large number of experiments have been conducted to establish a database of failure/no-failure conditions. Many experimental parameters (e.g., impact velocity, laminate thickness, ply arrangement, angle of impact, and projectile mass) were varied from experiment to experiment. Data from the penetration experiments were employed in the empirical modeling. Unfortunately, these empirical models cannot be used as predictive tools outside the tested velocity regimes and geometric configurations.

A two-dimensional (2-D) analytical model for penetration and perforation of homogeneous, isotropic target plates by rigid penetrators was developed by Ravid and Bodner (1983). That model is applicable for rigid penetrators and is completely self-contained, in that no empirical factors are required, and standard mechanical properties are utilized. The model involves five interconnected stages of the penetration and perforation process; where each is characterized by distinct geometrical features. Attention was given to the details of the failure mechanisms at the perforation condition.

There is considerable interest in developing a corresponding analytical model for targets composed of composite materials, such as glass fiber filaments or woven cloth in a polymer matrix, such as epoxy or polyester. The present report explores the possibility of adopting the dynamic plasticity model of Ravid and Bodner (1983) to analyze the penetration and perforation of rigid projectiles in targets of composite materials. In addition, this report presents a brief review of analytical/computational models that have been proposed to describe the penetration process in composite laminates and discusses the need for high strain rate characterization of polymeric composite materials.

Despite the basic anisotropy of the composite targets and that some of the mechanisms of penetration and failure differ from those of isotropic plates, it seems that the overall penetration patterns are similar for the two cases. Shortly after impact and a shock phase, which can probably be ignored for moderate impact velocities, except for the possibility of generating damage, there will be an initial stage of penetration in which target material forward of the projectile will be displaced and moved toward the impact surface. A zone of nonelastically deformed material (a plastic flow field in the case of metallic targets) will surround the projectile radially and longitudinally. When the front of that zone reaches the rear surface, the motion of the displaced target material will change direction and move forward to form a bulge on that surface. For metallic targets at that stage, a truncated conical or a cylindrical-like section of target material (i.e., a plug) generally forms forward of the projectile. Failure of material in the region between the projectile and the outer target surface will then lead to perforation of the target by plugging or tensile instability.

A complete qualitative description of the penetration and perforation process in laminated plates is given by Reid et al. (1995), who refer to unpublished reports by Greaves (1995) where the phases are considered: "Phase 1 involves compression, shear, indentation, and expulsion of debris. In phase 2 formation of a cone of delaminations, fiber stretching and fractures occur and the projectile exits from the back face."

For isotropic metallic target plates and not too high impact velocities, the resistance to penetration is due to inelastic deformation and inertial effects, and the same seems to be true for

composite plates. Delamination damage of the composite plates resulting from initial stress waves and the displacement of target material will also occur, but is not considered to be a major dissipation mechanism during the initial stage of ballistic penetration. It could, however, influence the effective strength of the target and would be an important factor in the residual strength of the perforated plate. Whether shock waves generated at initial impact are a significant factor for blunt-ended projectiles is uncertain. Shock wave effects generally can be ignored for metallic projectiles and targets when the impact velocity is less than 1,000 m/s. It is known that shock wave effects can be significant for ceramic targets, and their possible relevance for composite targets, such as laminated glass/epoxy, has to be examined, especially in relation to the possibility of generating damage. An analytical model for studying shock effects due to ballistic impact is described in Ravid, Bodner, and Holcman (1987) and can be exercised for a particular application.

A brief review of the main features of the dynamic plasticity penetration model of Ravid and Bodner (1983) is given in section 3, and the directions suggested for modification of the analytical model for application to composite targets are described. The overall objective is to formulate a fully contained 2-D analytical model for ballistic penetration and perforation of composite target plates normally impacted by rigid projectiles.

2. Background

This section provides a brief background on: (1) penetration mechanisms into composite targets, (2) related experiments, and (3) a review of analytical modeling efforts. Most of the penetration tests are traditionally performed at industries and Army laboratories, and the results are usually published as internal documents or in conference proceedings or government reports. The review provided here is mainly to serve as background material for our analytical model development effort and is not intended to be comprehensive.

2.1 Penetration Mechanisms. The mechanics of projectile penetration in fiber-reinforced composite targets is still not fully understood; however, several experimental investigations have

been undertaken to document the dominant failure mechanisms in composite targets (e.g., Bless et al. 1987). Bless et al. (1991) summarized various penetration mechanisms that develop in graphite/epoxy and S-2 glass/phenolic composites. The penetration and perforation process can be divided into three stages: impact, entry, and exit. In the impact phase, shock waves and elastic waves are generated in both the projectile and target. The maximum intensity of the shock wave depends on the impact velocity and the shock impedance of the target and projectile. Both waves could cause delamination of composite targets, possibly through spall-type failure. In the entry phase, the target material suffers mostly compressive failure in the contact region. The fibers and matrix fail around the penetration cavity.

The dominant failure mechanisms during the entry phase seem to be cutting of fibers due to shear and cavity expansion, which refer to the radial expansion of the target material away from the path of the projectile. This radial expansion is usually accompanied by local buckling of the fibers and microcracking of the matrix (epoxy) material. The fibers may undergo single shearing, where the fibers are cut only once, and the loose ends are left in the wake of the projectile; double shearing, where the fibers are cut twice and ejected from the penetration cavity; as well as kinking, due to compressive stresses during cavity expansion. The matrix suffers mostly compressive and shear failure during this stage.

In the exit phase, a transition from compressive failure to tensile or shear failure seems to occur, usually accompanied by extensive delamination. The time-dependent delamination process is initiated during the earlier time of the impact phase. However, the delamination growth (propagation) will continue until the arrival of the projectile near the delaminated areas. The plies are pushed ahead of the projectile, and tensile failure of fibers may occur away from the projectile nose. Fiber pullout may also occur in this stage. In the final exit mode, projectile energy is absorbed due to fiber failure, fiber pullout and delamination, as well as transfer of kinetic energy to the target. There is often extensive delamination accompanying fiber stretching. In general, the failure mechanisms involve fiber breakage, matrix cracking, ply cracking, delamination, and fiber pullout. It may not be practical to describe each and every one of these exit failure processes.

2.2. Experiments. For accurate modeling, the laminate strength variation, with respect to strain rate, has to be determined from high strain rate and shock-loading experiments. For this purpose, two experimental configurations are often considered: split Hopkinson bar (SHB) and plate impact tests. The SHB tests generate strength vs. strain rate data at strain rates above 200/s. The plate impact tests provide spall (dynamic tensile failure) strength and compressive strength at very high strain rates. Compressive strength at high strain rate is often calculated from the stress-gauge-measured steady-state value of the Hugoniot elastic limit (HEL), the stress amplitude at which inelastic deformation begins. Typically, one can identify the arrivals associated with the acoustic velocity, the compressive failure of the matrix, and the compressive failure of the fibers.

Chou and Deluca (1993) documented and summarized the results from high strain rate, as well as ballistic tests on GRP materials. There are only a few references in the open literature that involve studies on projectile penetration into composite armors (e.g., Bless, Krolak, and Askin 1985; Bless, Hartman, and Hanchak 1985). There are several material and impact parameters that can affect the penetration mechanisms, and one can systematically evaluate the effect of each parameter while keeping the other parameters constant. The key material parameters are the fiber, matrix, sizing, and lay-up, while the key impact parameters are impact velocity, projectile mass and nose shape, and the ratio of the target thickness to the projectile diameter. Presently, various types of fibers are available (e.g., graphite, glass, kevlar, spectra, etc.) that can be combined with suitable matrices (e.g., epoxies, phenolic, thermoplastics, etc.) to design laminates for practical applications.

2.3 Some Analytical Modeling Efforts. Modeling the penetration of a metal projectile into a composite laminate at high-velocity impact is extremely complex. Both the geometric and material responses are three-dimensional (3-D) and usually a 2-D axisymmetric idealization is not possible. Computational methods demand extensive computing resources, in terms of memory and CPU (central processing unit) time. While the advent of increased computing capabilities makes a computational approach feasible, there is a real need for analytical modeling. By invoking appropriate simplifying assumptions, mathematical complication can be minimized in the analytical modeling efforts. It would be useful if the penetration models developed for metal

targets could be adopted to describe penetration into composites. A major simplification in the penetration modeling of a homogeneous, isotropic target is achieved by invoking axisymmetry, and further simplification is obtained by assuming cylindrical cavity expansion, which reduces the problem to a one-dimensional (1-D) one. Such simplifications are generally not possible in the case of composite targets, but for quasi-isotropic laminates whose in-plane properties are isotropic, "restricted axisymmetry" can be assumed. A substantial simplification in the model can be realized by invoking a “plane strain" assumption, where the composite laminate target is idealized as a stack of thin, independent layers (plies), which are normal to the penetration direction. Incidentally, this same kinematic assumption has also been used in the penetration modeling of metal targets (e.g., Luk and Forrestal 1987).

Recently Lu and Vaziri (1994) presented an extensive review on constitutive and failure models for numerical analysis of the impact response of composite materials. In this report, they have cited the various papers that describe damage initiation and effects of damage on stiffness reduction. Several analytical approaches to modeling damage in composite laminates were also cited. Most of these studies were performed under either quasi-static loading or low-velocity impact conditions. For very high-velocity impact situations, the pressure in the region surrounding the penetrator is extremely high and greatly exceeds the strength of the target material. Typically, hydrodynamic theory is used in such cases to predict the depth of penetration and the deceleration of the penetrator. The basic hydrodynamic equations, developed mainly for elastic-plastic metallic targets, can be directly applied to composite targets; however, several fundamental issues need to be addressed. For instance, the pressure, R_t (Tate's model parameter [1967]), required for target material to undergo inelastic deformation, is generally a function of the impact velocity, depth of penetration, and a host of other factors, although some approximate results can be obtained by treating R_t as a material constant. Whether such an approach can be successful for composites is still an open question. Also, R_t has to be described from a physical standpoint based on a mechanistic model.

Pierson et al. (1993) developed an engineering approach to predict the dynamic penetration process of a rigid projectile into carbon fiber-reinforced plastic (CFRP). To describe the penetration force vs. time for a flat impactor into CFRP, the 1-D Awerbuch-Bodner model

(1974) was employed. The force vs. time history predicted by that model did not match well with the measurements, although the peak resistance force was reasonably well indicated. In the same paper, Pierson et al. (1993) extended the use of this model to describe the response of CFRP to conical projectile penetration with reasonable success. The predicted force vs. time history matched the experimental data.

Lee and Sun (1992) developed a model to predict the penetration process for composite laminates impacted by a blunt projectile. Under this study, a series of static punch tests was performed to study the mechanism of penetration. The test results showed that delamination and plugging were the primary failure mechanisms in the laminates, due to static penetration by a blunt projectile. This approach requires finite element modeling of the test configuration. The static penetration model is used to guide the simulation of the dynamic test. The ballistic limits of graphite/epoxy laminates were reasonably well predicted.

Using Whitney-Pagano (1970) laminated plate theory, Zhu, Goldsmith, and Dharan (1992a, 1992b) developed an analytical model suitable to predict the ballistic limits of laminates. The deformation and failure modes include: (1) a spherical bulging (as in the Ravid-Bodner [1983] model), (2) delamination, and (3) fiber extension (to predict fiber breakage). Matrix cracking was neglected in this model. The penetration stages consisted of indentation, perforation, and exit of the projectile. A finite difference computer program solving the governing equations of Whitney and Pagano (1970), in conjunction with the various failure criteria, was developed, and the ballistic limit of a Kevlar/polyester laminate was successfully predicted.

2.4 Computational Modeling. At present, the use of shock wave propagation-based finite element/difference "hydrocodes" to analyze projectile penetration into composite targets is restricted, due to the nonavailability of constitutive and failure models in these codes. Among the various general purpose 3-D codes, the DYNA3D code (Hallquist 1988) has an orthotropic material model with a damage description capability. Lu and Vaziri (1994) have cited a few limited attempts by various researchers to describe the response of composite materials to impact and penetration. Unfortunately those works failed to use an accurate equation of state (EOS) to account for the effects of anisotropy and were limited to quasi-isotropic or transversely

isotropic stress states and low-velocity regimes. Anderson et al. (1994) presented a detailed description of an elastic-plastic orthotropic model; this model has been implemented in the EPIC code (Johnson et al. 1994). Recently, Rajendran, Grove, and Anderson (1997) performed plate impact simulations to evaluate the model's ability to describe shock wave propagation in GRP materials.

3. Dynamic Plasticity Penetration Model

Here, the Ravid-Bodner model (1983) is adopted to predict the depths of penetration (DOP) in thick S2-glass fiber/polyester laminates due to a rigid steel projectile with a blunt nose. A full description of the original model and its modification to composite targets is given in the following sections.

3.1 The Analytical Approach. The basic approach of the dynamic plasticity analytical model of Ravid and Bodner (1983) is to enforce overall work-rate balance of the components of the system. That is equivalent to overall momentum balance, but does not require the detailed calculation of the specific forces acting on the projectile and is also amenable to approximation techniques. In particular, the inertial work rate of the projectile is taken to be equal to the work rates due to dissipation and the inertia of target material during the process. To calculate those work rates, the inelastic region is divided into convenient zones, and a deformation velocity field is assumed for each zone that has to meet the conditions of incompressibility, mass conservation, and velocity continuity normal to all boundaries of the zones and interfaces. Wave propagation and elastic effects are ignored, and the material is assumed to be viscoplastic, in that the flow stress is a function of plastic strain rate.

A sequence of five stages of the penetration and perforation process is identified, each of which is characterized by a particular deformation pattern (Figure 1 of Ravid and Bodner [1983] reproduced here as Figure 1). The first stage involves inelastic deformation zones surrounding the projectile radially and longitudinally within an overall cylindrical boundary (Figure 2 of Ravid and Bodner [1983] reproduced here as Figure 2).

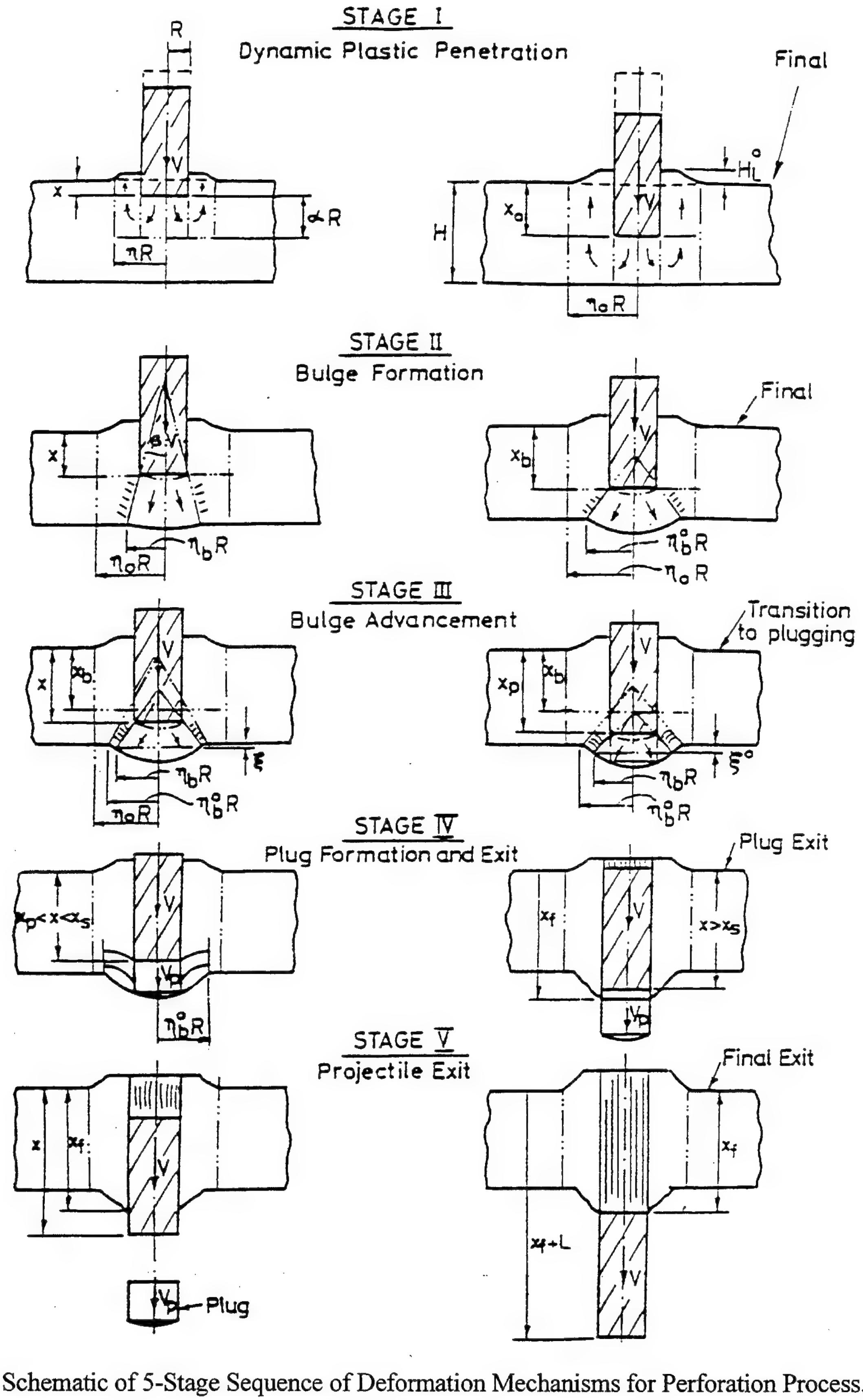

Figure 1. Schematic of 5-Stage Sequence of Deformation Mechanisms for Perforation Process.

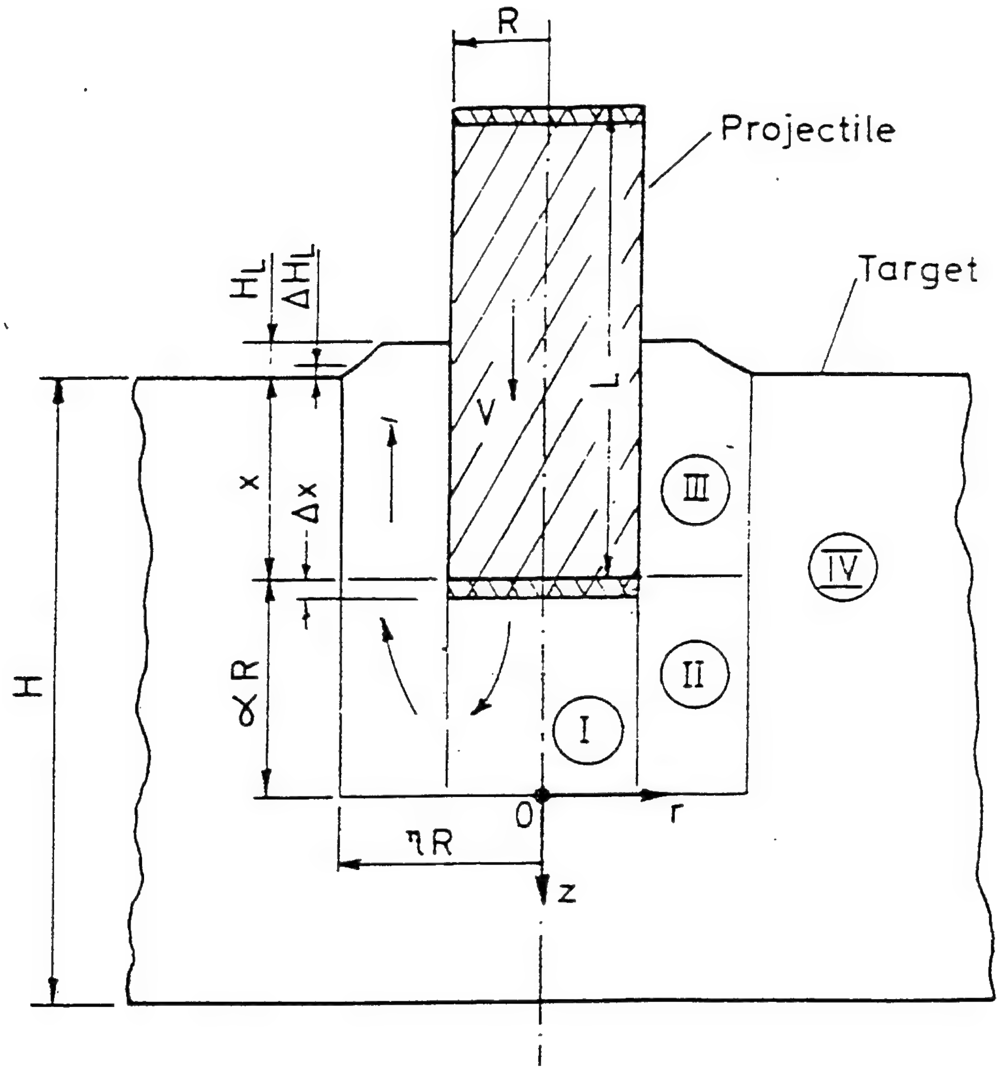

Figure 2. Plastic Flow Field for Stage 1 of Perforation Process - Dynamic Plastic Deformation.

The primary deformation mechanisms are cavity expansion in the radial direction and compression forward of the projectile. Material displaced by the projectile moves to the impact surface to form an entry lip. The deformation velocity field assumed by Ravid and Bodner (1983) is given here as Table 1.

Table 1. Particle Velocities and Strain Rates for Each Zone of the Plastic Flow Field Assumed During Stage 1 of the Penetration Process

Zone Notation (Figure 2)	Velocity Field: v_i			Strain Rate Field : $\dot{\varepsilon}_{ij}$			
	v_r	v_θ	v_z	$\dot{\varepsilon}_{rr}$	$\dot{\varepsilon}_{\theta\theta}$	$\dot{\varepsilon}_{zz}$	$\dot{\varepsilon}_{ij}$ for i = j
I	$\frac{vr}{2\alpha R}$	0	$-\frac{vz}{\alpha R}$	$\frac{v}{2\alpha R}$	$\frac{v}{2\alpha R}$	$-\frac{v}{\alpha R}$	0
II	$\frac{v(\eta^2 R^2 - r^2)}{2\alpha Rr(\eta^2 - 1)}$	o	$\frac{vz}{\alpha R(\eta^2 - 1)}$	$\frac{-v(\eta^2 R^2 + r^2)}{2\alpha Rr^2(\eta^2 - 1)}$	$\frac{v(\eta^2 R^2 - r^2)}{2\alpha Rr^2(\eta^2 - 1)}$	$\frac{v}{\alpha R(\eta^2 - 1)}$	0
III	0	0	$\frac{-v}{(\eta^2 - 1)}$	0	0	0	0
IV	0	0	0	0	0	0	0

The dissipation terms for stage 1 are due to straining over the volume of the inelastic deformation zone, shear straining on the boundaries of subzones, and friction on the projectile/target interfaces. Inertial effects in the target are due to convective and local acceleration of target material. The dimensions of the overall cylindrical boundary of the inelastic zone, αR and ηR (Figure 2), are determined by minimizing (at each increment of projectile displacement [or time]) the sum of the dissipative work rates of the target that includes the term due to convective acceleration of the target material. However, the summation does not include the term due to the local acceleration of target material that acts as an effective mass contribution to the projectile inertial term. The governing variational theorem for the minimization procedure has been proven in the appendix to Ravid, Bodner, and Holcman (1994b).

The first stage of penetration is completed when the front of the plastic flow zone reaches the rear surface. Subsequent to that condition, stage 2, material displaced by the projectile moves forward to form a bulge. A spherical bulge and a radial flow field forward of the projectile are assumed, as shown in Figure 1. The geometry is fully determined by mass conservation; so, a minimization procedure is not required for this and subsequent stages. At a certain condition of deformation, the spherical bulge shape ceases to operate and a change in deformation mechanism is required. A bulge advancement mode is introduced as stage 3, in which further displaced target material translates the original shape longitudinally to form a new spherical surface with a smaller radial extent as shown in Figure 1. Again, the geometry is fully determined by mass conservation.

Simultaneous with stages 2 and 3, a number of deformation modes are considered that could lead to failure. These include plug formation within the bulge region (stage 4) and the development of large shear strains along the truncated conical segment of the flow zone, which could be due to adiabatic shear band formation. In these cases, failure would be generated by the maximum shear strain reaching a limiting value. For very ductile target materials, tensile failure of the spherical cap along its periphery could occur. Plug ejection by any of the various possibilities followed by projectile exit is considered to be stage 5, which completes the process. It is noted that possible failure modes leading to perforation are not considered during stage 1 of the penetration process.

The penetration analysis of Ravid and Bodner (1983) was developed for a blunt nosed projectile. Since the original formulation was developed, a number of improvements have been incorporated into the analytical model. These are the consideration of conical, hemispherical, and ogival nose shapes, applicability of the model for all projectile length to diameter (L/D) ratios (previously, there were some limitations for small L/D ratios), consideration in stage 1 of possible movement of displaced target material into the cavity for deep penetrations, and thermo-mechanical coupling. These modifications have been published in Ravid, Bodner, and Holcman (1994a).

3.2 Modification for Composite Targets. The governing material properties for stage 1 of the isotropic dynamic plasticity penetration model are the compressive flow stress σ_Y for straining over the volume of the plastic flow region, and the shear stress τ_y due to shear straining at velocity discontinuities tangential to the subzone boundaries. In the case of isotropic materials, these can be related by $\sqrt{3}\,\tau_y = \sigma_Y$, according to the von Mises criterion. The flow stresses are taken to be linear functions of the logarithm of strain rate averaged over the respective regions. For application of the model to composite materials, a reasonable value for the shear flow stress τ_y would be that of the matrix material. The term τ_y should therefore be determined independently of σ_Y as a directly measured quantity or approximated by the matrix flow stress in shear.

Since the composite can be considered to have local orthotropic symmetry with orthogonal coordinate axes 1, 2, 3, the generalization of the von Mises isotropic yield function is given by Spencer (1991),

$$\frac{(\sigma_{11}-\sigma_{22})(\sigma_{11}-\sigma_{33})}{Y_1^2}+\frac{(\sigma_{22}-\sigma_{33})(\sigma_{22}-\sigma_{11})}{Y_2^2}+$$

$$\frac{(\sigma_{33}-\sigma_{11})(\sigma_{33}-\sigma_{22})}{Y_3^2}+\frac{\sigma_{23}^2}{K_1^2}+\frac{\sigma_{31}^2}{K_2^2}+\frac{\sigma_{12}^2}{K_3^2}=1 \qquad (1)$$

In equation (1), Y_1, Y_2, Y_3 could be interpreted as yield stresses for uniaxial compression (or tension, depending on the situation) in the x_1, x_2, x_3 directions, respectively. For composites, the yield values in compression are generally not the same as to those in tension. K_1 is the shear yield stress in the x_3 direction on the plane x_2 = constant and K_2 and K_3 have analogous interpretations. For the present application of a laminated plate, it would be reasonable to set $\tau_y = K_1 = K_2 = K_3$, and $Y_1 = Y_2$ where the x_1, x_2 axes are in the plane of the plate and the x_3 direction normal to it.

Another essential change in the calculation procedure would be that the work rate due to dissipation over the effected volume should separately consider the work rates due to the stress

components in the plane of the plate, σ_{rr} and $\sigma_{\theta\theta}$ (using cylindrical coordinates), and to the normal (i.e., longitudinal) stress σ_{zz}. In the case of stage 1 of the analytical model (i.e., prior to rear surface bulging), the coordinates that represent the strain rate field correspond to the principal axes of the material so that obtaining the expression for the dissipation is fairly direct. The in-plane stress components would have the material "flow" stress value $Y_1(=Y_2)$ while the normal (transverse) stress would correspond to Y_3. The expression for the work rate in a volume zone V_n would then be,

$$\dot{W}_V^n = \int_{V_n} \sigma_{ij}\,\dot{\varepsilon}_{ij}\,dV = \left\{Y_1\left[\left(\dot{\varepsilon}_{rr}\right)^{avg} + \left(\dot{\varepsilon}_{\theta\theta}\right)^{avg}\right] + Y_3\left(\dot{\varepsilon}_{zz}\right)^{avg}\right\}V_n \ , \tag{2}$$

where the symbol $\left(\dot{\varepsilon}_{ij}\right)^{avg}$ indicates an average value of the strain rate component in the zone. Ravid and Bodner (1983) provided expressions for the strain rate components for stage 1 as given in Table 1. The sum of the components is zero due to plastic incompressibility. Since the flow stress is a function of strain rate, the values Y_1, Y_3 , and τ_y should depend on associated average strain rates over the zone of interest.

Stages 2 and 3 of the penetration process involve inelastic flow fields with geometries that are complicated with respect to the material coordinates of the orthotropic target plate. In these stages, the shear effect is relatively more important so that some average value for the direct flow stress of the material may be adequate. Also, the failure strain for some composites such as glass fibers in polyester, is usually not large so that stage 1 can constitute the major resistance to ballistic perforation of such materials. With such an approximation, modification of the computer program developed for the analysis of Ravid and Bodner (1983) to apply to orthotropic target plates is reasonably straightforward insofar as other effects (e.g., damage due to stress waves) are not present. Prior to operating the fully modified program, some exercises were performed using a reasonably realistic value for τ_y and an overall average value for σ_Y in a program that only modified the shear flow stress from the isotropic case. The relevant material properties and dimensions for the reference tests are given in the appendix.

The first exercise (series 1) was the penetration of a blunt-nosed projectile of 12.7-mm diameter and 13.4-gm mass penetrating a 43.2-mm-thick laminated target plate at impact velocities ranging from 610 to 1220 m/s. The plate was constructed of layers of woven fiberglass with a polyester matrix. For this exercise, a simple average of Y_1 (230 MPa) and Y_3 (670 MPa) was used for σ_Y, namely 450 MPa, and τ_y was reduced from $\sigma_Y / \sqrt{3}$ by the factor 0.22, which corresponded to τ_y = 57 MPa. The strain to failure of the composite target was 7%, but this property is not utilized if material failure leading to perforation does not occur.

Six ballistic tests (two each at about 610, 915, and 1220 m/s) were run for this projectile, and the penetration depths were measured; there were no perforations for these tests. The test results and the predictions of the calculations are shown in Figure 3.

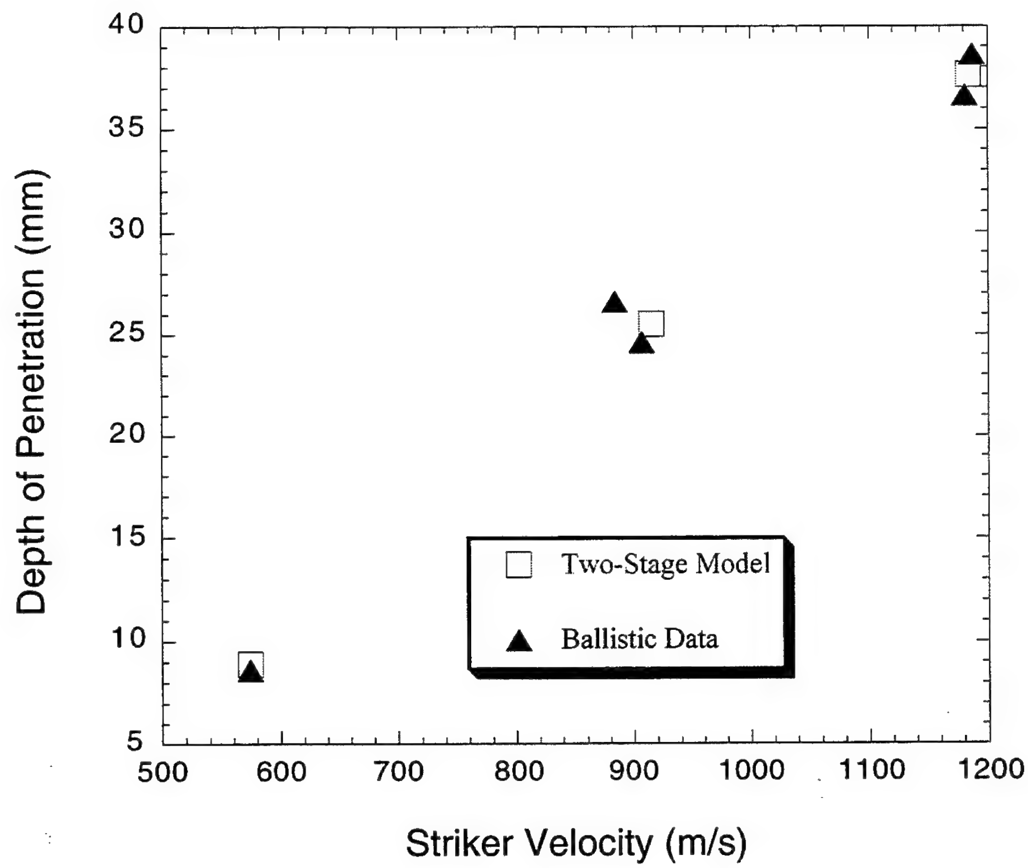

Figure 3. A Comparison Between the DOP Obtained From the 2-Stage Penetration Model and Ballistic Tests for a 13.4-gm Mass and 12.7-mm-Diameter Steel Projectile Penetration Into a 43-mm-Thick GRP Laminate.

It seems the agreement is very good despite the approximate nature of the reference analysis and the neglect of various mechanisms particular to composite target plates. A rationalization for the good agreement is that possible early delamination due to stress waves was not significant. Also, the use for the simple average of Y_1 and Y_3 implies that the factors on those strength terms in the volumetric work rate calculation were approximately the same. That is, the kinetic factors due to compression forward of the projectile and to cavity expansion in the in-plane direction were probably of similar magnitude in these cases.

In fact, a method for obtaining an average σ_Y for use in the subsequent penetration stages would be to weigh Y_1 and Y_3 by their respective kinetic factors in the expression for the volumetric dissipation rate in stage 1. It is also noted that spherical and conical-nosed projectiles would increase the relative contribution of the cavity expansion mechanism so that the average effective strength of the composite resisting penetration would be closer to the lower in-plane strength value.

A second set of tests with the same target plates as in the first series was performed with a larger projectile and impact velocities ranging from 430 to slightly over 790 m/s. This projectile was 20 mm in diameter with a mass of 54.26 g. With these conditions, the use of the simple average of Y_1 (230) and Y_3 (670) (namely 450 MPa) in the slightly modified analysis predicted penetration results that were lower than those of the tests (Figure 4). However, the use of a lower average strength value of 300 MPa and a shear strength of 38 MPa, based on the same factor (0.22) on the corresponding isotropic value, did lead to fairly good agreement (Figure 4).

A possible reason for the lower average strength exhibited in the second test series could be that the cavity expansion mechanism was relatively more important than that of forward compression for the larger diameter projectile. As such, the effective average strength would be dominated by the lower Y_1 value. Another possible reason for the lower strength is delamination damage forward of the projectile at some distance of penetration caused by stress waves reflected from the rear surface of the plate.

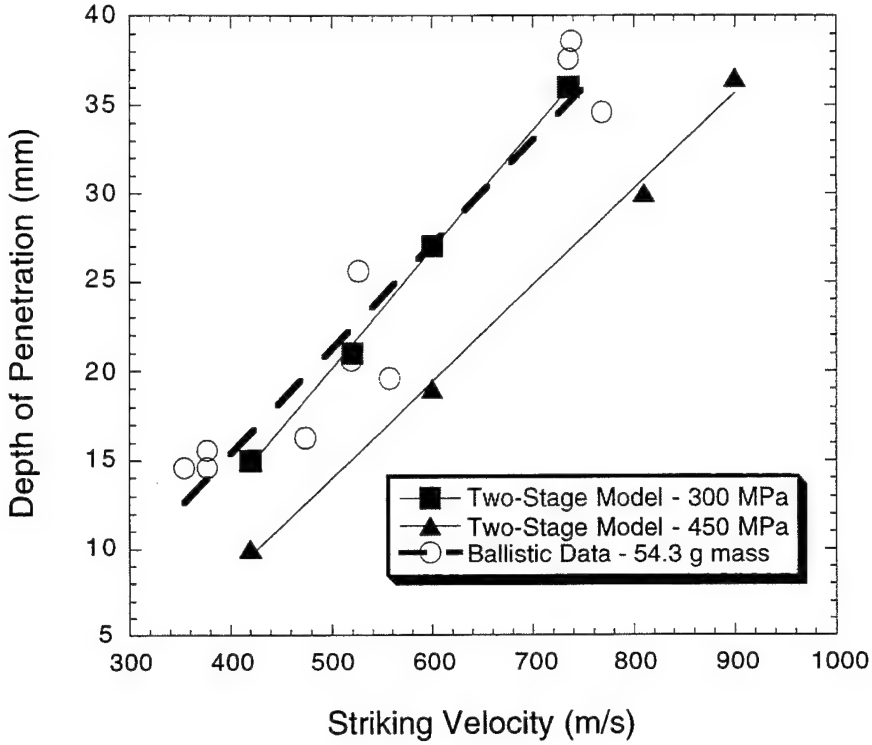

Figure 4. A Comparison Between the DOP Obtained From the 2-Stage Penetration Model and Ballistic Tests for a 54.3-gm Mass and 12.7-mm-Diameter Steel Projectile Penetration Into a 43-mm-Thick GRP Laminate.

The duration time of the stress wave would be greater for the longer and wider projectile with a higher probability of developing damage. Determining which mechanism is the more likely cause of the exhibited lower strength level requires further investigation. Specifically, the computer program for the analytical model of Ravid and Bodner (1983) should be modified to include equation (2) for the volumetric dissipation during stage 1. The investigation of possible damage due to stress waves could utilize the shock phase analysis of Ravid, Bodner, and Holcman (1987) or a simple elastic analysis to obtain the duration time and initial amplitude of the compressive elastic pulse traveling through the thickness of the target plate.

A failure criterion may be required to determine the damage developed by the reflected tensile wave. These two sets of exercises indicate that a simple average direct strength value and a reduced shear strength can serve in a slightly modified isotropic analysis to provide approximate to good predictions for penetration in composite target plates. Numerical exercises are still to be performed with the analysis modified for fully orthotropic material strengths.

4. Summary

The Ravid-Bodner (1983) model for ballistic penetration into isotropic targets was modified to predict the depths of penetration into thick S2-glass fiber/polyester laminates by blunt-nosed rigid steel projectiles. The directional properties could be introduced into the model during the different stages of the penetration process. A first approximation was to introduce a pseudo strength which was taken to be the average of the in-plane and transverse strengths of the laminates. Also the shear strength term has to be modified. The experimentally determined DOP were accurately predicted by the modified Ravid-Bodner (1983) model for a steel projectile with a mass of 13 gm. For tests with a heavier 54-gm projectile, modification of the pseudostrength value would be necessary to achieve good agreement. This indicates that the relative influence of the in-plane and transverse strengths would depend on the test conditions, as expected, and the model should be modified to more properly account for the different strength factors. A suggested procedure is given in this report.

A complete mechanistic-based model to describe the penetration process in composite laminates has yet to be developed. There are several reasons for the nonavailability of fundamental models: (1) Unlike metals, the behavior of composite laminates varies with geometry (thickness, fiber orientation, number of plies, etc.) and this geometry-influenced material property variation adds to the complexity of modeling the material behavior of composite laminates. (2) Since composite materials exhibit anisotropic behavior, most simplified analyses consider composite laminates only with some material symmetry, such as quasi-isotropic, transversely isotropic, etc. (3) Impact loading induces a very complex stress state, and analysis under such loading conditions is extremely difficult. (4) Metal projectile penetration into composites involves very complex failure processes, which are poorly understood. 6) Most penetration experiments provide only failure/no-failure conditions; nonavailability of time resolved measurements and carefully recovered targets from penetration experiments make evaluation of the failure sequence mostly speculative. (7) An extensive 3-D finite element analysis under dynamic loading conditions has not been considered until recently; however, with the advent of increased computer capabilities, this approach seems to be feasible.

5. References

Anderson, C. E., Jr., P. A. Cox, G. R. Johnson, and P. J. Maudlin. "A Constitutive Formulation for Anisotropic Materials Suitable for Wave Propagation Computer Programs - II." *Computational Mechanics*, vol. 15, pp. 201-223, 1994.

Awerbuch, J., S. R. Bodner. "Analysis of the Mechanics of Perforation of Projectiles in Metallic Plates." *International . Journal of Solids & Structures*, vol. 10, pp. 671-684, 1974.

Bless, S. J, S. J., Hanchak, K. Okajima, D. Hartman, and H. Sklyut. "Ballistic Penetration of S-2 Glass Laminates." 3rd Annual TACOM Armor Conference, Monterey, CA, 1987.

Bless, S. J., D. R. Hartman, B. Azzi, M. Benyami, D. Jurick. "Ballistic Penetration Study of S-2 Glass/Phenolic Spall Liner Materials." University of Dayton, Ohio, Unpublished work, 1991.

Bless, S. J., D. R. Hartman, and S. J. Hanchak. "Ballistic Performance of Thick S-2 Glass Composites." UDR-TR-85-88A, University of Dayton, Dayton, Ohio, 1985.

Bless, S.J., R. V. Krolak, and D. R. Askin. "Evaluation of Lightweight Materials for Shelter Armors." TR86/046L, Army Natick R&D Center, MA, 1985.

Chou, S.C., and E. Deluca. " Dynamic Response of S-2 Glass Reinforced Plastic Structural Armor - A Progress Report." ARL-SR-5, Army Research Laboratory, MA, 1993.

Greaves, L.J. Unpublished Report, Defence Research Agency, Chertsey, UK, 1992.

Hallquist, J.O. *DYNA3D User's Manual.* Lawrence Livermore National Laboratory, CA, 1988.

Johnson, G. R., R. A. Stryk, E. H. Petersen, T. J. Holmquist, J. A. Schonhardt, and C. R. Burns. "User Instructions for the 1995 Version of the EPIC Code." Alliant Techsystems Inc., Hopkins, Minnesota, 1994.

Lee, S-W. R., C. T. Sun. "Ballistic Limit Prediction of Composite Laminates by a Quasi-Static penetration Model." Proceedings of 24th Int. SAMPE Technical Conference, Eds. T. S. Reinhart, M. Rosenow, R. A. Cull, and E. Struckholt, vol. 24, 1992.

Lu, P. F., R. Vaziri. "A Review of Constitutive and Failure Models for Numerical Analysis of the Impact Response of Composite Materials." The University of British Columbia, Vancouver B.C., Canada,1994.

Luk, V. K., and M. J. Forrestal. " Penetration into Semi-infinite Reinforced Concrete Targets with Spherical and Ogival Nose Projectiles." *Journal. of Impact Engineering*, vol. 6, pp. 291-301, 1987.

Pierson, M. O., D. Delfosse, R. Vaziri, and A. Poursartip. "Penetration of Laminated Composite Plates due to Impact." Ballistics '93, vol. II, pp. 351-360, 1993.

Rajendran, A. M., D. J. Grove, and C. E. Anderson. "An Anisotropy Model to Describe the Shock and High Strain Rate Behaviors of GRP." U. S. Army Research Laboratory, Aberdeen Proving Ground, MD, in preparation, 1997.

Ravid, M., and S. R. Bodner. "Dynamic Perforation of Viscoplastic Plates by Rigid Projectiles." *International Journal of Engineering Sciences,* vol. 21, pp. 577-591, 1983.

Ravid, M., S. R. Bodner, and I. Holcman. "Analysis of Very High Speed Impact." *International Journal of Engineering Sciences*, vol 25, pp. 473-482, 1987.

Ravid, M., S. R. Bodner and I. Holcman. "A Two-Dimensional Analysis of Penetration by an Eroding Projectile." *International Journal of Impact Engineering*, vol. 15, no. 5, pp. 587-603,1994.

Ravid, M., S. R. Bodner, and I. Holcman. "Penetration into Thick Targets - Refinement of a 2D Dynamic Plasticity Approach." *International Journal of Impact Engineering*, vol. 15, no. 4, pp. 491-499, 1994.

Reid, S. R., T. Y. Reddy, H. M. Ho, I. G. Crouch, and L. J. Greaves. "Dynamic Indentation of Thick Fiber-Reinforced Composites." High Strain Rate Effects on Polymer, Metal, and Ceramic Matrix Composites and Other Advanced Materials, vol. 48, ASME, 1995.

Spencer, A. J. M. "Thermoelastic-Plastic Deformations of Orthotropic Materials." *Anisotropy and Localization of Plastic Deformation*, Eds. J.P. Boehler, A.S. Khan, Elsevier Applied Science, Pub. London, pp. 28-31, 1991.

Tate, A. " Theory for the Deceleration of Long Rods After Impact " *Journal of Mechanics and Physics of Solids*, vol. 15, pp 387-399, 1967.

Whitney, J. M., and N. J. Pagano, "Shear Deformation in Heterogeneous Anisotropic Plates." *Journal of Applied Mechanics*, vol. 37, pp. 1031-1036, 1970.

Zhu, G., W. Goldsmith, C. K. H. Dharan. "Penetration of Laminated Kevlar by Projectiles - I, Experimental Investigation." *International Journal of Solids & Structures*, vol. 29, no. 4, pp. 399-420, 1992a.

Zhu, G., W. Goldsmith, and C. K. H. Dharan. "Penetration of Laminated Kevlar by Projectiles - II - Analytical Model." *International Journal of Solids & Structures*, vol. 29, N0. 4, pp. 421-436,1992b.

INTENTIONALLY LEFT BLANK.

Appendix:
Ballistic Tests

INTENTIONALLY LEFT BLANK.

Properties of composite target plates (fiberglass-polyester)

density: 1.93 g/cm^3 ; thickness: 43.2 mm

in-plane compressive strength: 230 MPa

transverse (normal) compressive strength: 670 MPa

strain to failure: 7%

strain rate sensitivity coefficient: 0.005 (assumed)

Properties of projectiles (blunt nosed cylinders)

series 1 (impact velocities, 2000-4000 ft/s)

density: 7.850 g/cm^3

mass: 13.42 g

diameter: 12.70 mm

length: 13.50 mm

series 2 (impact velocities, 1400-2600 ft/s)

density: 7.850 g/cm^3

mass: 54.26 g

diameter: 20.0 mm

length: 22.0 mm

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ DENNIS SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	CECOM SP & TRRSTRL COMMCTN DIV AMSEL RD ST MC M H SOICHER FT MONMOUTH NJ 07703-5203
1	PRIN DPTY FOR TCHNLGY HQ US ARMY MATCOM AMCDCG T M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	PRIN DPTY FOR ACQUSTN HQS US ARMY MATCOM AMCDCG A D ADAMS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	DPTY CG FOR RDE HQS US ARMY MATCOM AMCRD BG BEAUCHAMP 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	ASST DPTY CG FOR RDE HQS US ARMY MATCOM AMCRD COL S MANESS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

NO. OF COPIES	ORGANIZATION
1	DPTY ASSIST SCY FOR R&T SARD TT F MILTON THE PENTAGON RM 3E479 WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT D CHAIT THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT K KOMINOS THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT B REISMAN THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT T KILLION THE PENTAGON WASHINGTON DC 20310-0103
1	OSD OUSD(A&T)/ODDDR&E(R) J LUPO THE PENTAGON WASHINGTON DC 20301-7100
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DUSD SPACE 1E765 J G MCNEFF 3900 DEFENSE PENTAGON WASHINGTON DC 20301-3900
1	USAASA MOAS AI W PARRON 9325 GUNSTON RD STE N319 FT BELVOIR VA 22060-5582

NO. OF COPIES	ORGANIZATION
1	CECOM PM GPS COL S YOUNG FT MONMOUTH NJ 07703
1	GPS JOINT PROG OFC DIR COL J CLAY 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	ELECTRONIC SYS DIV DIR CECOM RDEC J NIEMELA FT MONMOUTH NJ 07703
3	DARPA L STOTTS J PENNELLA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	SPCL ASST TO WING CMNDR 50SW/CCX CAPT P H BERNSTEIN 300 O'MALLEY AVE STE 20 FALCON AFB CO 80912-3020
1	USAF SMC/CED DMA/JPO M ISON 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MDN A MAJ DON ENGEN THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	<u>ABERDEEN PROVING GROUND</u>
2	DIR USARL AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
5	DEFENSE NUCLEAR AGENCY MAJ J LYON CDR K W HUNTER T FREDERICKSON R J LAWRENCE SPSP K KIBONG 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
3	COMMANDER US ARMY ARDEC AMSTA AR FSA E W P DUNN J PEARSON E BAKER PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH V M D NICOLICH PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC E ANDRICOPOULOS PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA STRATEGIC DEFNS CMD CSSD H LL T CROWLES HUNTSVILLE AL 35807-3801
2	COMMANDER US ARMY MICOM AMSMI RD ST WF D LOVELACE M SCHEXNAYDER REDSTONE ARSENAL AL 35898-5250
1	MIS DEFNS & SPACE TECHNOLOGY CSSD SD T K H JORDAN PO BOX 1500 HUNTSVILLE AL 34807-3801

NO. OF COPIES	ORGANIZATION
4	COMMANDER US ARMY BELVOIR RD&E CTR STRBE N B WESTLICH STRBE JMC T HANSHAW STRBE NAN S G BISHOP J WILLIAMS FORT BELVOIR VA 22060-5166
2	COMMANDER US ARMY RESEARCH OFFICE K IYER J BAILEY PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	NAVAL RESEARCH LAB A E WILLIAMS CODE 6684 4555 OVERLOOK AVE SW WASHINGTON DC 20375
1	NAVAL AIR WARFARE CTR S A FINNEGAN BOX 1018 RIDGECREST CA 93556
3	COMMANDER NAVAL WEAPONS CENTER T T YEE CODE 3263 D THOMPSON CODE 3268 W J MCCARTER CODE 6214 CHINA LAKE CA 93555
1	NAVAL POST GRADUATE SCHOOL PHYSICS DEPARTMENT J STERNBERG MONTEREY CA 93943
2	AIR FORCE ARMAMENT LAB AFATL DLJW W COOK M NIXON EGLIN AFB FL 32542

NO. OF COPIES	ORGANIZATION
5	U.S. ARMY TANK AUTOMOTIVE RESEARCH DEVELOPMENT & ENGINEERING CENTER K BISHNOI AMSTA-TR-R, MS: 263 WARREN, MI 48397-5000
2	USAF PHILLIPS LABORATORY PL WSCD FIROOZ ALLAHDADI PV VTA D SPENCER 3550 ABERDEEN AVE SE KIRTLAND AFB NM 87117-5776
11	DIRECTOR SANDIA NATL LABS E S HERTEL JR MS 0819 J ASAY MS 0458 R BRANNON MS 0820 L CHHABILDAS MS 0821 D CRAWFORD MS 0821 M FURNISH MS 0821 P TAYLOR ORG 1432 M KIPP DIV 1533 P YARRINGTON DIV 1533 M FORRESTAL DIV 1551 R GRAHAM DIV 1551 PO BOX 5800 ALBUQUERQUE NM 87185-0307
7	DIRECTOR LLNL M J MURPHY N C HOLMES W TAO L282 P URTIEW L282 A HOLT L290 J E REAUGH L290 W J NELLIS L299 PO BOX 808 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
5	DIRECTOR LANL D MANDELL J SHANER MS F670 R DAVIDSON MS K557 J JOHNSON G787 F ADDEGGIO G787 PO BOX 1663 LOS ALAMOS NM 87545
1	JET PROPULSION LAB M ADAMS IMPACT PHYSICS GROUP 4800 OAK GROVE DR PASADENA CA 91109
3	CALTECH A INGERSOLL MS 170 25 PROF G RAVICHANDRAN T J AHRENS MS 252 21 1201 E CALIFORNIA BLVD PASADENA CA 91125
1	GEORGIA INSTITUTE OF TECHNOLOGY COMPUTATIONAL MODELING CENTER S ATLURI ATLANTA GA 30332-0356
1	NC STATE UNIVERSITY YASUYUKI HORIE RALEIGH NC 27695-7908
1	SOUTHWEST RESEARCH INSTITUTE C ANDERSON PO DRAWER 28510 SAN ANTONIO TX 78284
2	UNIVERSITY OF DELAWARE DEPT OF MECHANICAL ENGINEERING PROF J GILLESPIE PROF J VINSON NEWARK DE 19716

NO. OF COPIES	ORGANIZATION
1	VIRGINIA POLYTECHNIC INSTITUTE COLLEGE OF ENGINEERING R BATRA BLACKSBURG VA 24061-0219
1	ADVANCED TECHNOLOGY INC J ADAMS PO BOX 125 DAHLGREN VA 22448-0125
1	ALLIANT TECHSYSTEMS INC T HOLMQUIST MN11 2720 G R JOHNSON MN11 2925 600 SECOND ST NE HOPKINS MN 55343
1	COMPUTATIONAL MECHANICS CONSULTANTS J A ZUKAS PO BOX 11314 BALTIMORE MD 21239-0314
2	INST OF ADVANCED TECHNOLOGY UNIVERSITY OF TX AUSTIN S J BLESS T M KIEHNE 4030-2 W BRAKER LN AUSTIN TX 78759
1	KAMAN SCIENCES CORP D L JONES 2560 HUNTINGTON AVE SUITE 200 ALEXANDRIA VA 22303
1	KAMAN SCIENCES CORP J S WILBECK 600 BLVD S SUITE 208 HUNTSVILLE AL 35802
1	ORLANDO TECHNOLOGY INC D A MATUSKA PO BOX 855 SHALIMAR FL 32579

NO. OF COPIES	ORGANIZATION
2	SRI INTERNATIONAL DR L SEAMAN DR D CURRAN 333 RAVENSWOOD AVE MENLO PARK CA 94025
3	TELEDYNE BROWN ENGR J W BOOTH M B RICHARDSON PO BOX 070007 MS 50 HUNTSVILLE AL 35807-7007
	ABERDEEN PROVING GROUND
19	DIR, USARL AMSRL-WM, I. MAY AMSRL-WM-T, W. F. MORRISON AMSRL-WM-TA, J. DEHN W. A. GOOCH H. W. MEYER AMSRL-WM-TC, K. KIMSEY D. SCHEFFLER AMSRL-WM-PD, G. GAZONAS AMSRL-WM-WD, A. PRAKASH AMSRL-WM-MF, A RAJENDRAN (5 CP) D GROVE (5 CP)
5	DIR, USARL AMSRL-WM-TD, A M DIETRICH M RAFTENBERG G RANDERS-PEHRSON M SCHEIDLER T WRIGHT

NO. OF COPIES	ORGANIZATION
1	ABTEILUNG FUER PHYSIKALISCHE CHEMIE MONT ANUNIVERSITAET E KOENIGSBERGER A 8700 LOEBEN AUSTRIA
2	AWE M GERMAN W HARRISON FOULNESS ESSEX SS3 9XE UNITED KINGDOM
1	BATTELLE INGENIEUTECHNIK GMBH DUESSELDORFFER STR 9 ESCHBORN D 65760 GERMANY
1	BHABHA ATOMIC RESEARCH CENTRE HIGH PRESSURE PHYSICS DIVISION N SURESH TROMBAY BOMBAY 400 085 INDIA
1	BULGARIAN ACADEMY OF SCIENCES SPACE RESEARCH INSTITUTE VALENTIN GOSPODINOV 1000 SOFIA PO BOX 799 BULGARIA
1	CANADIAN ARSENALS LTD P PELLETIER 5 MONTEE DES ARSENAUX VILLIE DE GRADEUR PQ J5Z2 CANADA
1	CEA R CHERET CEDEX 15 313 33 RUE DE LA FEDERATION PARIS 75752 FRANCE

NO. OF COPIES	ORGANIZATION
1	CEA CISI BRANCH P DAVID CENTRE DE SACLAY BP 28 GIF SUR YVETTE 91192 FRANCE
1	CEA/CESTA A GEILLE BOX 2 LE BARP 33114 FRANCE
3	CENTRE D'ETUDES DE GRAMAT S GERARD C LOUPIAS PASCALE OUTREBON GRAMAT 46500 FRANCE
2	CENTRE D'ETUDES DE LIMEIL-VALENTON C AUSSOURD J BOZIER S G CEDEX VILLENEUVE 94195 FRANCE
3	CENTRE D'ETUDES DE VAUJOURS P JEAN-PAUL E BOTTET TAT SIHN VONG BOITE POSTALE NO 7 COUNTRY 77181 FRANCE
1	CENTURY DYNAMICS LTD N FRANCIS 12 CITY BUSINESS CTR BRIGHTON RD HORSHAM WEST SUSSEX RH1354BA UNITED KINGDOM
1	CRC RESEARCH INST INC M KATAYAMA STRUCTURAL ENGINEERING DEPT 1 3 316 NAKASE MIHAMA KU CHIBA SHI 261 01 JAPAN

NO. OF COPIES	ORGANIZATION
1	DAT ETBS CETAM C ALTMAYER ROUTE DE GUERRY BOURGES 18015 FRANCE
1	DEFENCE RESEARCH AGENCY W A J CARSON CHOBHAM LANE CHERTSEY SURREY KT16 0EE UNITED KINGDOM
1	DEFENCE RSCH ESTAB SUFFIELD D MACKAY RALSTON ALBERTA TOJ 2NO RALSTON CANADA
1	DEFENCE RSCH ESTAB SUFFIELD C WEICKERT BOX 4000 MEDICINE HAT ALBERTA TIA 8K6 CANADA
1	DEFENCE RSCH ESTAB VALCARTIER N GASS PO BOX 8800 COURCELETTE PQ GOA IRO CANADA
4	DEPARTMENTO DE QUIMICA FISICA FACULTAD DE CIENCIAS QUIMICAS UNIVERSIDAD COMPLUTENSE DE MADRID V G BAONZA M TARAVILLO M CACERAS J NUNEZ 28040 MADRID SPAIN
1	DYNAMIC RESEARCH AB A PERSSON PARADISGRAND 7 SODERTALJE S 151 36 SWEDEN

NO. OF COPIES	ORGANIZATION
4	ERNST MACH INSTITUT VOLKER HOHLER E SCHMOLINSKE E SCHNEIDER A J STILP ECKERSTRASSE 4 D-7800 FREIBURG I BR 791 4 GERMANY
1	ESTEC CS D CASWELL BOX 200 NOORDWIJK 2200 AG NETHERLANDS
1	EUROPEAN SPACE AGENCY W FLURY ESOC 5 ROBT BOSCHT STRASSE DARMSTADT 6100 GERMANY
2	EUROPEAN SPACE AGENCY ESTEC L BERTHOUD M LAMBERT POSTBUS BOX 299 NOORDWIJK NL2200 AG NETHERLANDS
1	FRENCH GERMAN RESEARCH INST H F LEHR POSTFACH 1260 WEIL AM RHEIN D-79574 GERMANY
3	FRENCH GERMAN RESEARCH INST H ERNST F JAMET PASCALE LEHMANN CEDEX 5 5 RUE DU GENERAL ASSAGNOU SAINT LOUIS 68301 FRANCE

NO. OF COPIES	ORGANIZATION
4	HIGH ENERGY DENSITY RESEARCH CTR V E FORTOV G I KANEL V A SKVORTSOV O YU VOJOBIEV IZHORSKAJA STR 13/19 MOSCOW 127412 RUSSIAN REPUBLIC
5	IABG H J RAATSCHEN W SCHITTKE F F SCHARPPF M BORRMANN H G DORSCH EINSTEINSTRASSE 20 D 8012 OTTOBRUN B MUENCHEN GERMANY
1	INSTITUTE FOR PROBLEMS OF STRENGTH G STEPANOV TIMIRYAZEVSKAYU STR 2 252014 KIEV UKRAINE
1	INSTITUTE OF CHEMICAL PHYSICS A YU DOLGOBORODOV KOSYGIN ST 4 V 334 MOSCOW
3	INSTITUTE OF CHEMICAL PHYSICS RUSSIAN ACADEMY OF SCIENCES A M MOLODETS S RAZORENOV A V UTKIN 142432 CHERNOGOLOVKA MOSCOW REGION RUSSIAN REPUBLIC
2	IOFFEPHYSICO TECHNICAL INST DENSE PLASMA DYNAMICS LABORATORY E M DROBYSHEVSKI A KOZHUSHKO ST PETERSBURG 194021 RUSSIAN REPUBLIC

NO. OF COPIES	ORGANIZATION
1	IPE RAS A A BOGOMAZ DVORTSOVAIA NAB 18 ST PETERSBURG RUSSIAN REPUBLIC
1	ISL CHANTERET PIERRE-YVES F68301 SAINT-LOUIS CEDEX 12 RUE DE I'INDUSTRIE BP 301 FRANCE
1	LABORATOIRE DE TECHNOLOGIE DES SURFACES ECOLE CENTRALE DE LYON P VINET BP 163 69131 ECULLY CEDEX FRANCE
2	LAVRENTYEV INST. HYDRODYNAMICS L A MERZHIEVSKY V V SILVESTROV NOVOSIBIRSK 630090 RUSSIAN REPUBLIC
1	MOSCOW INST OF PHYSICS & TECH S V UTYUZHNIKOV DEPT OF COMPUTATIONAL MATHEMATICS DOLGOPRUDNY 1471700 RUSSIAN REPUBLIC
1	NATL DEFENCE DENSITY RSCH CTR J FORSS FOA FOX 551 TUMBA S 14725 SWEDEN
3	NATL DEFENCE RESEARCH EST L HOLMBERG ULF LINDEBERG LARS GUNNAR OLSSON FOA BOX 551 TUMBA S 14725 SWEDEN

NO. OF COPIES	ORGANIZATION
1	PML TNO E VAN RIET BOX 45 RIJSWIJK 2230AA NETHERLANDS
1	PRB S A M VANSNICK AVENUE DE TERVUEREN 168 BTE 7 BRUSSELS B 1150 BELGIUM
1	PRINS MAURITS LABORATORY H J REITSMA TNO BOX 45 RIJSWIJK 2280AA NETHERLANDS
1	RAFAEL BALLISTICS CENTER DR Z ROSENBERG PO BOX 2250 HAIFA 31021 ISRAEL
1	RESEARCH INSTITUTE OF MECHANICS NIZHNIY NOVGOROD STATE UNIVERSITY A SADYRIN P R GAYARINA 23 KORP 6 NIZHNIY NOVGOROD 603600 RUSSIAN REPUBLIC
1	ROYAL ARMAMENT R&D ESTAB I CULLIS FORT HALSTEAD SEVENOAKS KENT TN14 7BJ UNITED KINGDOM
1	SAMARA STATE AEROSPACE UNIV L G LUKASHEV SAMARA RUSSIAN REPUBLIC

NO. OF COPIES	ORGANIZATION
1	TECHNISCHE UNIVERSITAT MUENCHEN E B IGENBERGS RICHARD WAGNER STR 18 111 MUENCHEN 2 D8000 GERMANY
1	TOMSK BRANCH OF THE INST FOR STRUCTURAL MACROKINETICS V GORELSKI 8 LENIN SQ GSP 18 TOMSK 634050 RUSSIAN REPUBLIC
1	TU CHEMNITZ-ZWICKAU L MEYER FAKULTAET FUER MASCHINENBAU U. VERFAHRENSTECHNIK SCHEFFELSTRASSE 110 09120 CHEMNITZ GERMANY
1	UK MINISTRY OF DEFENCE G J CAMBRAY CBDE PORTON DOWN SALISBURY WITTSHIRE SPR 0JQ UNITED KINGDOM
1	UNIVERSIDAD DE CANTABRIA FACULTAD DE CIENCIAS DEPARTMENTO DE FISICA APLICADA J AMOROS AVDA DE LOS CASTROS S/N SANTANDER SPAIN
1	UNIVERSIDAD DE OVIEDO FACULTAD DE QUIMICA DEPARTMENTO DE QUIMICA FISICA Y ANALITICA E FRANCISCO AVENIDA JULIAN CLAVERIA S/N 33006 - OVIEDO SPAIN

NO. OF COPIES	ORGANIZATION
1	UNIVERSITY OF GUELPH PHYSICS DEPT C G GRAY GUELPH ONTARIO N1G 2W1 CANADA
2	UNIVERSITY OF KENT UNIT FOR SPACE SCIENCES PHILIPPE GENTA PAUL RATCLIFF CANTERBURY KENT CT2 7NR UNITED KINGDOM

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1997	Final, Oct 95 - Sep 96

4. TITLE AND SUBTITLE

Application of an Analytical Model for Ballistic Penetration to Composite Targets

5. FUNDING NUMBERS

6MPCER

6. AUTHOR(S)

S. R. Bodner* and A. M. Rajendren

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-MF
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-1383

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

U.S. Army Tank Automotive Research, Development, and Engineering Center
Warren, MI 48397-5000

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Israel Institute of Technology, Haifa 32000, Israel

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This report presents the procedures developed for adopting a two-dimensional (2-D) analytical model of ballistic penetration and perforation in isotropic targets to target plates of composite materials (e.g., glass [fiber] reinforced plastics [GRP]). The depths of penetration in S-2 glass fiber/polyester matrix composite laminates were calculated using this analytical model and compared with the measured data. The initial formulation is based on blunt-nosed rigid projectiles and normal impact velocities up to about 1 km/s. Some preliminary results are described, and directions for further investigations are indicated. This report also briefly reviews penetration mechanisms in GRP laminates and some experiments and analytical/computational modeling efforts by other investigators.

14. SUBJECT TERMS

composite, ballistic, modeling, penetration, DOP, GRP, polymers

15. NUMBER OF PAGES

39

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1383 (Bodner) Date of Report June 1997

2. Date Report Received ______

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL WM MF
ABERDEEN PROVING GROUND MD 21005-5069